# HIGH VOLTAGE BREAKDOWN STRENGTH OF RAPID PROTOTYPE MATERIALS*

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## *Abstract*

We report measurements on the breakdown strength of plastics used in stereo lithography for rapid prototyping. Three epoxy-based photopolymer resins commonly used for stereo lithography were the focus of this work. Test samples were manufactured with an electrically smooth geometry to minimize field enhancements. The thickness of the stressed region in the samples was nominally 1 or 2 mm. Samples were tested to failure by applying a ramped and held voltage pulse at discrete levels up to a maximum of 240 kV. We confirmed the uniform field distribution of the sample geometry with electrostatic modeling and calculated the electric field stress at failure as a simple voltage/thickness ratio. These results are compared with values obtained for several typical materials often used in high voltage applications (acrylic, nylon, etc.). We find that the failure threshold for the SLA materials can be a factor of 2-3 below that of the standard materials.

## I. INTRODUCTION

The complexity of high voltage breakdown processes in solid materials is significantly greater than in gases. As a result, engineers are often forced to use empirical information about the electrical breakdown strength of materials for guidance concerning minimum feature size. Any time a new family of materials becomes available, measurements should be made with practical physical arrangements and voltage characteristics to establish the high voltage properties of import to the designer.

One such family of materials is associated with the rapid prototyping technology of stereo-lithography, commonly referred to as SLA. This technology allows a design to transition very quickly from a computer-aided design (CAD) model to a functional part. SLA uses photopolymer resins cured through the application of ultraviolet laser energy to produce solid three-dimensional objects. A part is "grown" by using data from a solid modeling CAD program to control the UV laser as it cures successive cross-sections of liquid resin. Typically, SLA is used for prototype development and other materials are used to manufacture the final pieces. [1] However, there are a number of situations in which it might be desirable to use the SLA produced part as the finished product, particularly when speed of availability is a factor. Therefore, it is helpful to understand the impact on high voltage performance from process variations and/or material choices made during SLA part production.

Three epoxy-based photopolymer resins commonly used in SLA were the focus of this work. Each has unique mechanical properties, such as tensile strength and flexure. These known material properties can also be influenced somewhat by various processing parameters such as the build layer thickness and the post-build cure parameters. We present results from an investigation of the electrical breakdown strength of solid materials produced by SLA processes. These results are then compared with values obtained for several typical materials often used for high voltage equipment manufacture (acrylic, nylon, etc.). We find that the failure threshold for the SLA materials can be as much as a factor of 2 to 3 below that of the standard materials.

## II. EXPERIMENTAL SETUP

The American Society for Testing and Materials (ASTM) provides guidance for breakdown studies of materials in the form of numerous standard test methods. The most applicable standard for this work is ASTM standard D3755-97 entitled "Standard Test Method for Dielectric Breakdown Voltage and Dielectric Strength of Solid Electrical Insulating Materials Under Direct-Voltage Stress." ASTM D3755-97 addresses all aspects of testing, including use of information, apparatus, safety precautions, breakdown criteria, specimen geometry, number of tests, preparation of samples, ambient conditions, procedures for applying voltage, and reporting requirements. In general we followed the ASTM guidance directly. The only significant deviation was in the method of voltage application, described below.

### *A. Sample Geometry*

One of the main features required of a test sample is that it should force a breakdown event as opposed to surface flashover. Figure 1 shows a cross-sectional view

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and photos of a typical test sample. The overall dimensions of the samples were 9.5 cm in diameter and 9 mm at the tallest. The central region of the sample is the area under test with a flat area 4.1 cm in diameter and a 4.5 mm radius transition to a ridge feature. The thickness of the flat area was chosen to be nominally 1 or 2 mm. Stainless steel electrodes were machined to match the geometry of the inner area. Electrostatic modeling showed the transitions at the electrode edges were smooth enough that no field enhancements were generated.

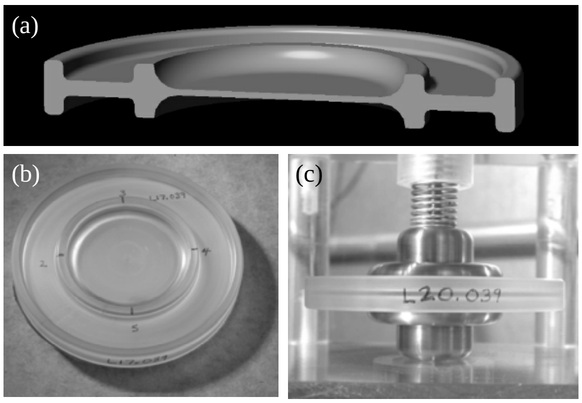


**Figure 1**. Pictures showing (a) the cross sectional view of a sample disk, (b) typical sample, and (c) sample and electrodes mounted in test chamber.

### *B. Sample Materials*

Three SLA materials were examined for this work. These materials are made by DSM Somos® and have material parameters optimized for different purposes.

- Somos® 7120 is a general-purpose resin that produces amber-colored parts with high rigidity and tolerance for heat and humidity.
- Somos® 9120 has properties similar to polypropylene and can produce robust functional parts.
- Somos® 10120 is similar to acrylic in that it is transparent and can produce strong rigid parts.

Samples from each of these materials were manufactured by an SLA parts supplier based on our electronic CAD files. The parts were grown with a 355 nm solid-state laser using a layer thickness step size of 0.1 mm. The samples were grown in the optimal direction (round cross-sections) to minimize “rasterized” features on curved edges from the layer steps. Samples were typically post-processed by curing under an ultraviolet lamp and may also have been “cleaned up” with minor machine work to meet the mechanical specifications.

The SLA samples as delivered displayed variations in thickness across the center region, so each sample was measured at five locations with a caliper and the thickness was taken as the average of the measurements.

The samples also displayed material non-uniformity. Figure 2 shows a picture of a 9120 sample with normal lighting and a back-lit image of the same piece which has been contrast enhanced. There are a number of obvious features including a line across the sample and a regular array of spots in the center region. These intensity changes probably correspond to density or thickness variations in the material.

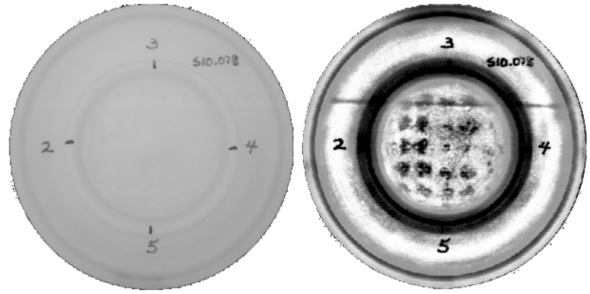


**Figure 2**. Pictures of a 9120 sample with normal lighting (left) and with contrast enhanced backlighting (right).

For comparison purposes samples were also made from acrylic, polycarbonate (Lexan®), Nylon 66, and Torlon® using bulk materials and standard machining methods. The machined quality of these samples was excellent except for the Nylon 66. The center of each Nylon sample was bowed-out rather than flat and the center of the electrically stressed region was always thicker than the outside perimeter.

### *C. Sample Preparation*

Prior to failure testing each sample was prepared in an identical manner. The samples were cleaned for 15 minutes in an ultrasonic cleaner with a 1% Alconox® solution. They were then rinsed with 1 liter of 18 MΩ-cm deionized water, blown dry with filtered air, and stored in a container with desiccant until needed for testing.

### *D. Applied Voltage Profile*

The dielectric breakdown strengths quoted for typical plastics can vary anywhere between 10 and 100 kV/mm, with the predominant values around 20 kV/mm. Since we were examining test samples with 1 and 2 mm thickness it was thought sufficient to set up a test capability of at least 200 kV. This was accomplished using positive and negative Spellman SL600 power supplies each rated to 120 kV. The sample assembly was mounted in a pressurized test chamber and isolated from nearby ground. The high voltage output from each supply was connected to one of the sample assembly electrodes, resulting in a bipolar configuration capable of applying up to 240 kV across the thin section of the sample. The test chamber was evacuated and then pressurized with 60 PSIG of Sulfur Hexaflouride to help prevent surface flashover around the sample perimeter.

The applied voltage profile for these experiments is the only significant deviation from methods specified in ASTM D3755-97. The standard calls for applying voltage at a constant ramped rate of 500 Volts per second (V/s) until the sample fails. This rate was too slow to be of interest for our particular applications in which there are charge rates of 10’s of kV in less than a second.

The method we chose to stress the samples was to apply a series of quasi-DC “pulses” that were ramped up to a specified voltage level in one second, held at that level for an additional one second, and then allowed to fall rapidly back to zero. Figure 3 shows a typical set of applied voltage data. The positive and negative power supplies were slaved together and controlled by an external program voltage. The top graph of Figure 3 shows the program voltage waveform into the power supplies and the resulting monitor signal return. The bottom graph shows measured values on the positive and negative electrodes as well as the total voltage applied across the sample for this experiment. The experimental voltage envelope follows the program envelope reasonably well on the rising feature, but the power supplies would only allow the falling edge to decay exponentially with a time constant of about 1 second. The one-second ramp up and one-second hold envelope always remained the same, and there were 72 discrete voltage peak levels that could be selected with this experimental setup, with a minimum waveform peak of 9.6 kV and a maximum of 240 kV.

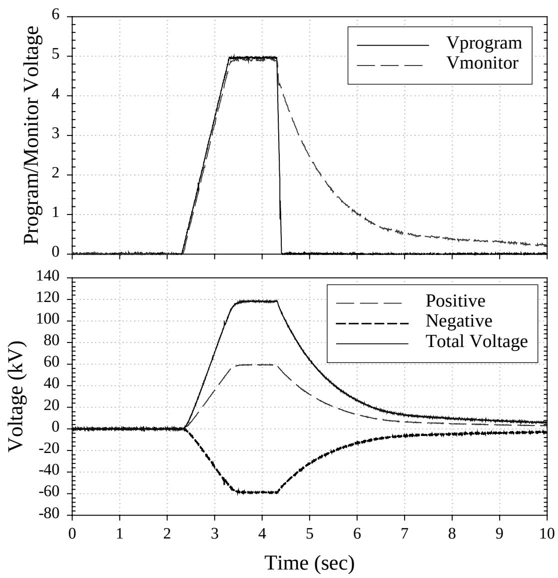


**Figure 3**. Control signals (top graph) and measured voltages (bottom graph) for a 120 kV experiment.

### *E. Experimental Procedure*

For each material a minimum of 5 samples were experimentally evaluated, in accordance with ASTM D3755-97. The first sample of each material type was subjected to a series of 10-pulses starting at the lowest peak voltage of 9.6 kV. If the sample did not fail within these 10 pulses then the voltage peak was raised to the next available level and another 10 pulses were applied. This sequence continued until the sample either failed by punch-through or surface flashover limited further testing. For subsequent samples in the material set the starting voltage was arbitrarily set to be 60% of the lowest measured failure level of that material. This was done because samples that failed at high field levels required hundreds of pulses if the starting point was always the lowest voltage. The applied voltage was monitored on every pulse to check whether the failure occurred during the ramp or at the peak.

## III. EXPERIMENTAL RESULTS

Figure 4 shows a typical waveform measured when a sample failed 0.8 seconds into the 1-second peak-hold period. This waveform is typical in that the failure occurred during the voltage-hold portion of the cycle, not on the ramp. The image in Figure 4 shows the physical spot on the sample where the sample failed. Breakdown was always indicated by signal variations in the monitor waveform, an arc indication by the power supplies, and an obviously damaged location on the sample.

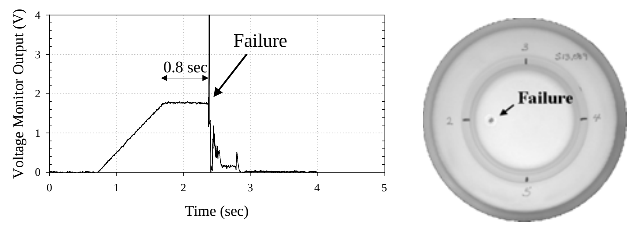


**Figure 4**. Graph of a typical waveform measurement for a failure event and an image of the corresponding punch-thru on the sample.

The first sample of each material set was typically exposed to more pulses because the experiment was started at the lowest available voltage. This is shown in the graph of Figure 5 for the set of five samples of 1 mm thick Torlon material. Sample #1 was exposed to 331 total pulses before it failed at 177 kV. Testing on sample #2 started at 105 kV (60% of 177 kV) and it was only exposed to 133 pulses before it failed at 168 kV. The starting point for sample #3 was adjusted accordingly, etc.

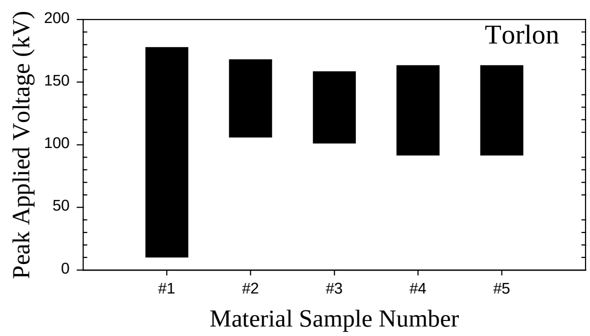


**Figure 5**. Graph showing the range of voltage exposure for 5 samples of nominal 1 mm Torlon.

A question raised by this experimental technique is whether the different treatment of the first sample affects the measured result. It would seem that the exposure to more pulses would make it likely that the first sample would fail at a lower level than the rest, but this is not borne out in the data shown in Figure 5. The first sample in fact has the highest breakdown level.

Figure 6 shows range-of-exposure data from two batches of the nominal 1 mm thick SLA 9120 material. Batch A was manufactured just before testing and Batch B was manufactured approximately one year prior to the actual failure tests. These two batches were treated as different materials and so the first sample of each set was started at the lowest voltage. Note that the first sample in

Batch A displayed the highest failure voltage in the A-group, but the first sample in Batch B displayed the lowest failure level for the B-group. In general we found no trend indicating a bias induced by this methodology.

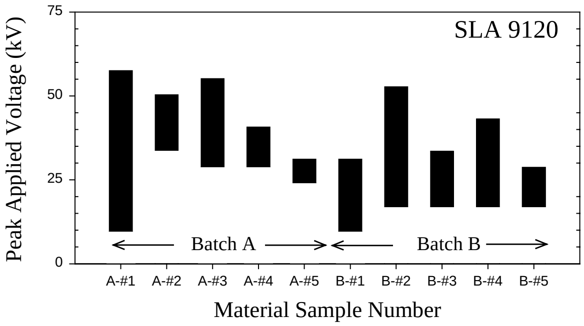


**Figure 6**. Graph showing the range of voltage exposure for samples in two different batches of nominally 1 mm thick 9120 material.

Figure 7 shows a summary graph of the minimum, average, and maximum electric field levels at failure for all the SLA materials tested for this report. The electric field was calculated by taking the voltage at failure divided by the average thickness of the sample. Included are the two different batches of the 1 mm thick 9120 material. Also included is the only data on 2 mm thick samples (9120 material) that we were able to acquire prior to the generation of this report.

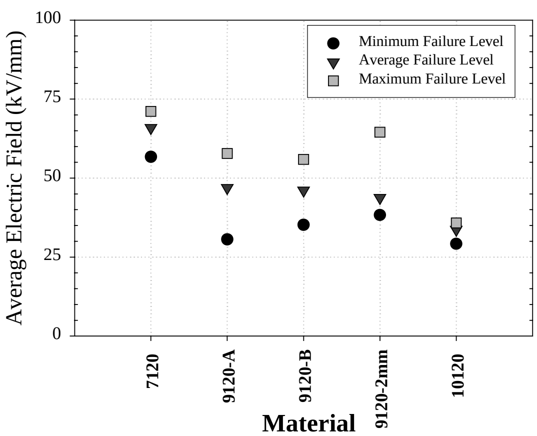


**Figure 7**. Graph showing the minimum, maximum, and average electric field at failure for all the SLA samples. All materials were 1 mm thick except for the 2 mm 9120 set noted in the axis label.

The data show that the 7120 material was the best SLA performer in terms of average breakdown strength at approximately 65 kV/mm. The 9120 material displayed a consistent average of 45-48 kV/mm across all three batches of 1 mm and 2 mm thick material, although with significant spread from min. to max. The 10120 material was the worst performer with an average breakdown level of 33 kV/mm. However, this last measurement looks quite favorable as compared with the value of 15 kV/mm for 10120 from the manufacturers product specifications.

Figure 8 shows a summary graph of the minimum, average, and maximum electric field levels at failure for the standard materials evaluated in this effort. Note that the vertical axis for the electric field values is much higher in Figure 8. All the standard materials were nominally 1 mm thick.

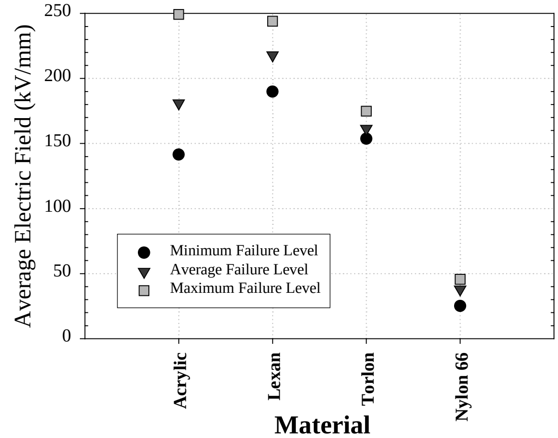


**Figure 8**. Graph showing the minimum, maximum, and average electric field at failure for 1 mm thick standard material samples.

It is apparent from comparison of Figure 7 and Figure 8 that in general the machined standard materials perform significantly better than the SLA. Acrylic, Lexan, and Torlon all exhibit average breakdown levels above 150 kV/mm. The only anomalous result is from the Nylon 66, which exhibited average breakdown strength of only 37 kV/mm. This was consistent across the five Nylon samples as evidenced by the low spread from minimum to maximum. This was not expected, as there are numerous published values of breakdown strength for Nylon that indicate the value should meet or exceed that of the other standard materials. The Nylon samples were the worst in terms of fit in the test assembly because of the bow in the center section and thickness variations, so it is possible that this contributed to the low failure levels.

## IV. SUMMARY

We described experimental results comparing the dielectric breakdown strength of SLA materials with standard materials. We found that SLA materials fared poorly, averaging around 50 kV/mm at failure. The standard materials achieved consistently greater than 150 kV/mm before breakdown, except for Nylon 66, which failed at even lower levels than the SLA materials. It is apparent that if SLA materials are used in high voltage apparatus this difference must be taken into account.

## V. REFERENCES

[1] Paul Jacobs, Stereolithography and other RP&M Technologies: from Rapid Prototyping to Rapid Tooling. American Society of Mechanical Engineers, New York, New York, 1996